Modeling and Simulation of Basochhu Hydropower Plant: Islanding Operation Using Real-Time Performance Data

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Abstract

This paper presents the dynamic modeling and simulation of the 64 MW Basochhu Hydro investigation of its island mode operation and network restoration. A robust real-time simulation model is necessary to analyze the static and dynamic control and operating characteristics of hydropower plant, which can be empirically modeled based on real-time performance measurements. The schematic layout of the BHP from the reservoir (pond) to the turbine is divided into sub-components, each of which is represented by mathematical differential-integral equations. The composite model was then validated by comparing the simulated and real-time measured responses. The paper also examined the preliminary test results of island mode operation and restoration to grid connection. The midnight load of Thimphu was arranged for island operation taking into account of the minimal power disruption. At the instant of grid disconnection, the active power of the test unit fell freely from 13 MW to 9 MW, activating the deflector control instantly cutting off the water jets proportional to the power drop. The measurements and simulation results confirmed that the Basochhu Hydropower Plant has robust governor control systems, and it can withstand the island mode operation, and reliably feed the local load without the need for grid interconnection.

Keywords – Hydropower, measurement, modelling, MatLab/Simulink, Island mode

Introduction

Bhutan has fast-flowing rivers, and an estimated technically and economically viable hydropower potential of 23,760 MW (Bhutan Power System Master Plan 2040, 2019). With the commissioned of 700 MW Mangdechhu in 2019, a total installed capacity is increased to 2326 MW (Annual Report 2019, DGPC). Almost 70% of total energy generated is exported to India accounting 25% of the country's annual revenue. Four additional power plants (PHPA-I and II, Nikachu and Kholongchu) are currently under construction and will add an additional 2,938 megawatts of power upon completion.

The hydropower plants are operated, controlled, and managed by Druk Green Power Corporation Limited (DGPCL), a state-owned power generation corporation. DGPC faces ongoing challenges such as maintaining power quality, stability, reliability, and protection controls associated with power plants and transmission networks (Tala HPP Model Report, 2015). Hence, it is advisable to adopt scientific and advanced technical methods of investigation by developing the robust dynamic modeling and simulation of hydropower plant. Thus, from 2014 to 2016, a team comprised of DGPC, College of Science of Technology (CST), Bhutan Power Corporation (BPC), and the University of Rostock, Germany, completed the project 'Analysis and Modeling of Bhutan's Hydropower Plants for Investigations Using Dynamic Simulation' to investigate the performance of hydropower plants on the overall behaviours, in both grid-connected and the islanded operation. In addition, it brought the transfer of know-how and the building of in-house capabilities of students, faculty, and power system operators.

The collaborative team measured the performance of the following hydropower plants (HPPs), developed and analyzed the dynamic Simulink models:

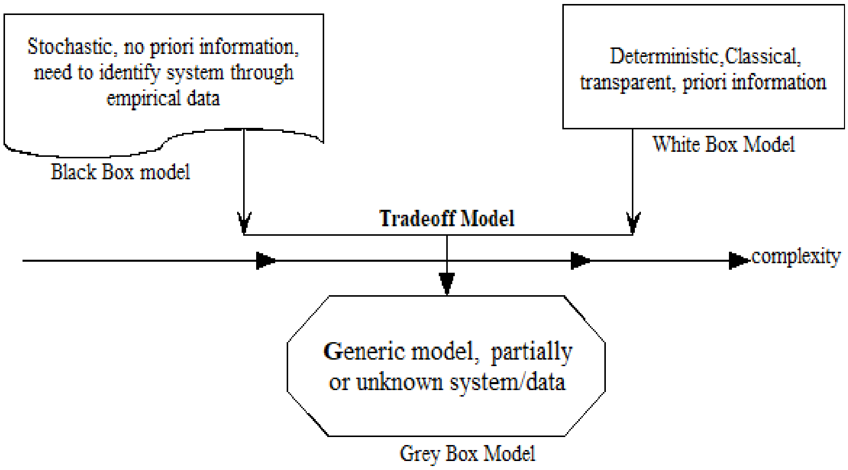
1) 1020 MW, Tala Power Plant (2014-2015)
2) 336 MW, Chukha Power Plant (2015-2016)
3) 60 MW, Kurichu Power Plant (2016-2017)

The project, however, came to an end in mid-2017 with the physical measurement of the 64 MW, BHP, allowing CST, DPGC, and BPC's in-house partners to complete BHP's systematic dynamic modeling and analysis. Therefore, this paper demonstrates the modeling and simulation performance of BHP and its stability of island mode operation.

Literature Review; Hydropower Dynamic Modelling and Simulation

The principles of control system engineering and the theoretical approach to mathematical models are essential for beginners in physical modeling and simulation. The two forms of mathematical modeling are first-principles modeling and system identification, or a combination of the two (Ljung et al., 1994). Researchers often combine the two approaches because it is easier to derive a generic model from first principles and determine the unknown parameters empirically using measured data (Kurt-Erik, 2017). On the other hand, any accurate real-time modeling is difficult as each modeling approach is different, so a trade-off modeling approach is often adopted. A realistic computer model should closely resemble an actual system and accurately simulate the expected behaviour or properties of a physical system (Ljung, 1987). According to its complexity and prior knowledge of the physical process, modeling methods are also divided into a black box, white box, and grey box modeling, (Ducard, 2017) as shown in Figure 01.

Figure 01: Types of Modelling based on the degree of complexity (source: wikipedia.org/wiki/Mathematical_model)



The modeling of hydropower plant is broadly categorized into linear and nonlinear models, according to classical control system theory (Kishor, Sania, & Singh, 2005). Based on real-time dynamic modeling and simulation of hydropower in Macedonia and Serbia, the hydropower simulation model can be constructed empirically using experimental test data (Holst, Golubovic & Weber, 2007; Weber & Prillwitz, 2003).

The paper on Dynamic Modeling and Simulation of 1020 MW Tala Hydropower Plant in Bhutan (Holst, et al., 2015) describes a schematic layout of the hydropower Plant divided into subcomponents and represented by mathematical differential equations and Simulink blocks. Simulink blocks are then sequentially interconnected to form a generic mathematical model, which is then further trained and simulated using real-time measurement data.

The comprehensive dynamic modeling and simulation of hydropower plant connected with transmission networks (Holst, Pradhan, & Dorji, 2016) demonstrated that the hydraulic parts of hydropower can be modeled and fine-tuned in Matlab/Simulink and then interfaced with the transmission network built-in DigSilent Power factory.

Area of Study: Basochhu Hydropower Plant (BHP)

Basochhu Hydropower Plant (BHP) is located in the western part of Bhutan, with a catchment area of 225 square kilometres that contains two tributaries of the Punatsangchhu basin; Basochhu and Rurichhu. BHP is the country's first and only cascading power plant, designed by the Austrian government.

The power plant has a total installed capacity of 64 MW and is divided into two stages: a 12x2 MW upper stage and a 20x2 MW lower stage (Figure 03). The pond (Figure 02) formed by the tailrace of the upper stage is fed to the lower stage through a 2.53 km long penstock.

The Upper Stage was commissioned in 2001 and followed by Lower Stage in 2004. The power plant produces an average of 290 million units of energy annually. The operation and control settings of both stages are fully automated with the supervisor control and data acquisition (SCADA) system. The generated power is evacuated via 220kV and 66kV transmission lines connected to the western grid of Bhutan (Operation and Maintenance Handbook, (BHP), 2016).

Figure 02: Pond reservoir

Figure 03: Powerhouse of the lower stage, 20x2 MW

The Modeling of Hydraulic System (BHP)

The schematic diagram of a typical hydropower plant consists of reservoir, water channel, surge chamber, penstock, turbine, governor control system, and power grid. The hydropower plant models can be divided into linear (inelastic) and nonlinear (elastic) categories, with or without surge tanks (Kishor, Sania, & Singh, 2005). The hydraulic system of BHP is modeled and simulated as a nonlinear system without a surge tank but combined with the influence of the water column as highlighted in Figure 04.

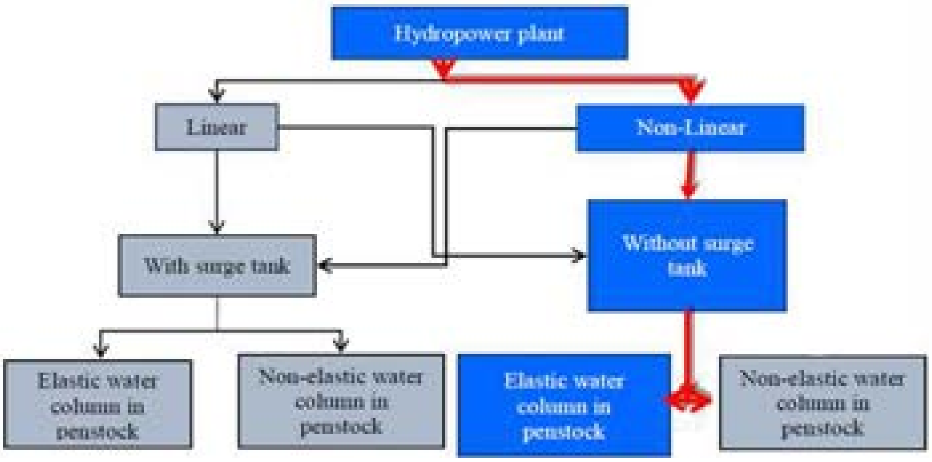


Figure 04: Classification of Hydropower plant models

The BHP model is developed and simulated based on the algorithm chart shown in

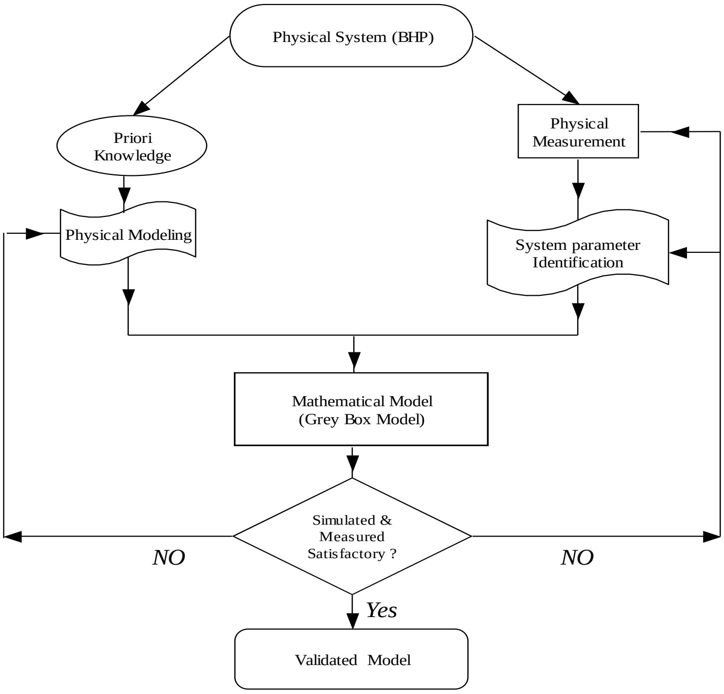


Figure 05: Flowchart for Modelling and Simulation

The lower stage of the BHP was chosen for measurement and for its higher plant capacity compared to the upper stage. The hydraulic system of the lower stage consists of a 74000 m^3 reservoir pond and 2.53 km long penstock linked to twin turbines (Figure

06) with the total discharge rate of 10 m^3/s (Operation and Maintenance Handbook, (BHP), 2016).

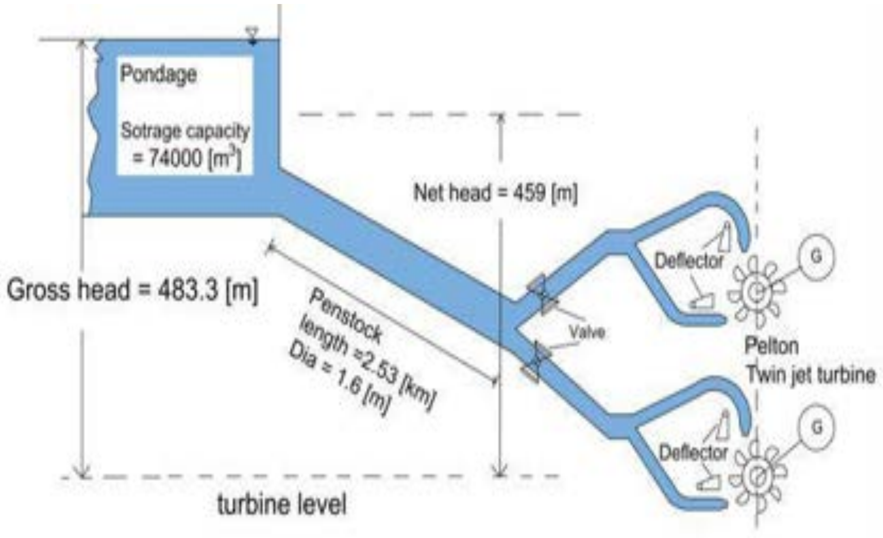


Figure 06: Schematic diagram of water hydraulic path of the lower stage

A non-linear model of a hydraulic system without a surge tank could be derived using the reservoir-based approach of energy conversion (Holst, et al., 2015). The pressure difference between inlet and outlet of penstock determines the flow rate (q_{out}) which can be expressed mathematically as an equation (1)

$$q_{out} = \frac{1}{T_{wps}} \int (h_{ow} - h_{edr})\, dt \qquad (1)$$

The head loss in penstock due to friction and water hammer effect is estimated as

$$\Delta h = h_{edr} - h_{ow} = k_{fps} \times (q_{out})^2 \qquad (2)$$

The effect of water compressibility (h_{edr}) at inlet valve is represented by the difference in flow rates in penstock;

$$h_{edr} = \frac{1}{T_{cps}} \int (q_{in} - q_{out})\, dt \qquad (3)$$

Where

q_{out} and q_{in} are the flow rate of output and input of penstock

T_{wps} and T_{cps} are the time constants of water starting and compressibility in the penstock

$h_{ow},\ hedr,$ and Δh are the water head at reservoir level, at the turbine and the frictional head loss at the penstock.

k_{fps} is the friction factor aiding the head loss at the penstock.

Figure 07 illustrates the simplified Simulink model of hydraulic path of the lower Stage obtained from the integration of above equations (1), (2) and (3).

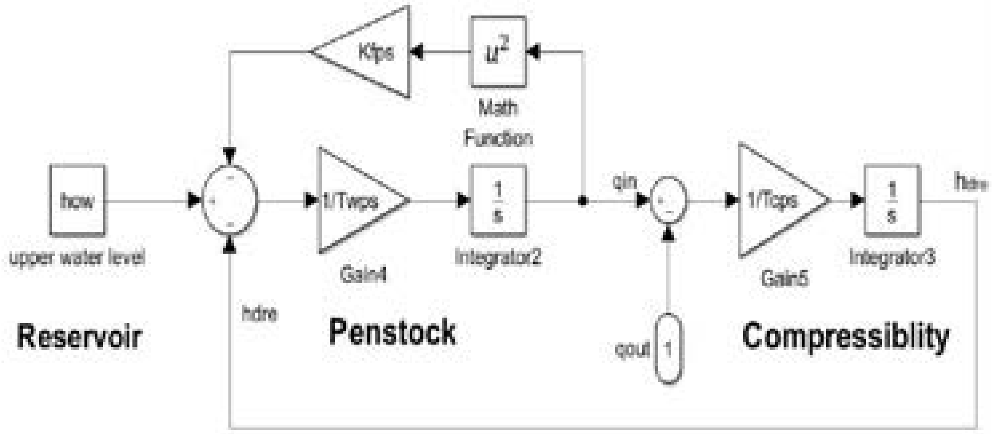


Figure 07: Sub-model of water hydraulic part of BHP

The time constants of hydraulic system were calculated using the physical dimensions and parameters acquired from the measurements shown in Table (01).

Table 01: time constant parameters of the hydraulic system

T_{wps} (seconds)	T_{cps}(seconds)	k_{fps}
2.7946	1.2390	0.0467

Turbine Simulink Model (BHP)

The operation of turbine is controlled by a digital governor system that uses needle and deflector actuators to measure water flow, start and stop the turbine, and regulate generator speed and power output.

The mechanical power of the turbine is expressed as a function of flow rate (q), pressure head (h), and turbine efficiency (η) given in equation (4).

$$p_m = f(q, h, \eta) \qquad (4)$$

According to Torricelli equation, the flow discharge at the turbine is given by equation (5).

$$q = a\sqrt{h} \qquad (5)$$

where a is nozzle opening/closing area.

The mathematical modeling of the turbine is too complex as it involves many non-linear variables. Nonetheless, the turbine characteristics derived from the Hill Charts are the most accurate models (Luz, 2010). The Hill chart is the turbine operating curve typically provided by the manufacturer. The nonlinear turbine parameters, such as mechanical output power, head, and efficiency, were retrieved from the Hill chart's various operating points, creating a three-dimensional lookup table (Holst et al., 2015).

However, the Hill chart for the BHP turbine is not available and its model is derived from another Hill chart (Figure 08), which has identical operating characteristics. The operating points were appropriately rescaled and interpolated to generate a 3-D curve of BHP turbine (Figure 09).

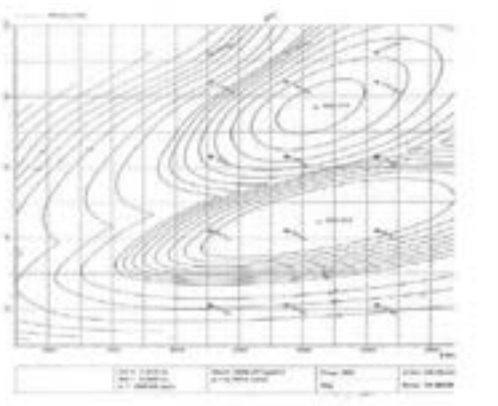


Figure 09: Typical Hill Chart

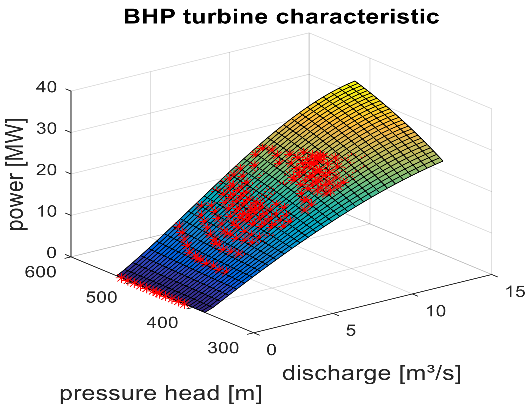


Figure 09: Extracted Hill Chart, BHP turbine

Nozzle and Deflector System Modeling

Figure 10 shows the nozzle and deflector arrangement of a pelton turbine controlled by a digital governor and hydraulic servo motor system. The nozzle consists of a pipe, an orifice, a needle, and a positioning cylinder that controls the water jet. The nozzles must open quickly as the generator output changes. However, it should be closed gradually to minimize the effects of water compressibility in the penstock (Operation and Maintenance Manual, (BHP), 2016).

Figure 10: Nozzle Needle and Cut-in Deflector (divider type)

In the case of grid instability, the active power oscillates and the generator speed deviates from the normal range. In order to prevent this runaway speed, the cut-in deflector must act quickly to divert some or all of the water jet from the runner bucket (Operation and Maintenance Manual, (BHP), 2016).

The mathematical models for the nozzle and deflector are defined by their polynomial function of opening and closing area given by equation (6) and the coefficient values were obtained from the dry stoking test measurements (Holst, et al., 2007).

$$aT = -0.1109{Y_t}^2 + 1.125Y_t - 0.020 \qquad (6)$$

where

aT is nozzle opening and closing area, Y_t is needle position, Y_D is deflector position and a_D is the deflector area.

Figures 11 and 12 illustrates the mathematical Simulink blocks of nozzle and deflector movements.

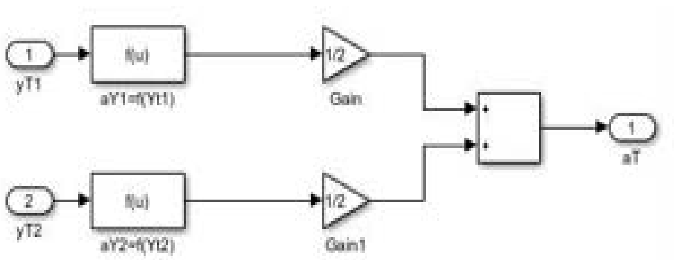


Figure 11: Simulink model of nozzle movement

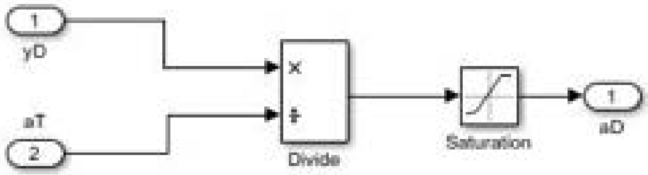


Figure 12: Simulink model of delfector movement

Real-time Performance Measurements

The accuracy of mathematical modeling depends on the actual input data, which can be obtained by physical measurements. Different sets of experiments were performed on Unit-I of Lower Stage (BHP) to determine various electrical and mechanical operating set points, such as voltage/reactive power limits, active power and frequency, and opening/closing position of nozzles and deflector. A total of 23 measurement files, each containing 11 different signals, were recorded using LabVIEW™ data acquisition system (DAQ) connected to the computer, as shown in Figure 13 and 14.

Figure 13: LabVIEW™ Instruments

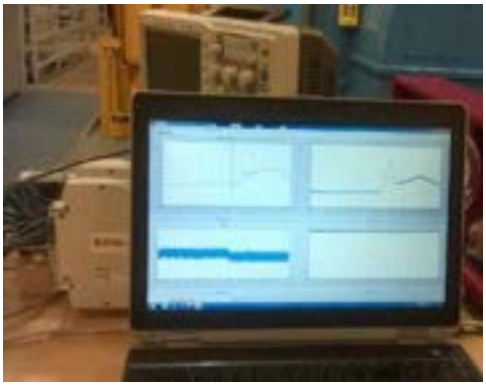


Figure 14: Real-time logging of signals

The following is a list of performance measurements taken under various hydropower plant operating scenarios;

1. Active power loading/de-loading test

With an initial load of 1.18 MW, the active power of the test unit was increased in smaller steps, followed by larger steps of 4 to 5 MW, and vice versa, while decreasing load in steps. Figure 15a and 15b show the response of all signals, including the active power of the second unit.

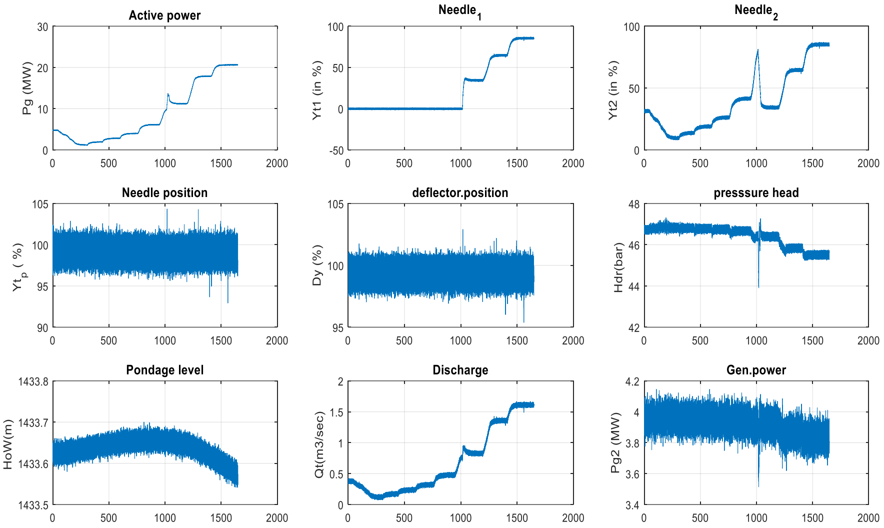


Figure 15a: Signal responses when the load is increased in steps.

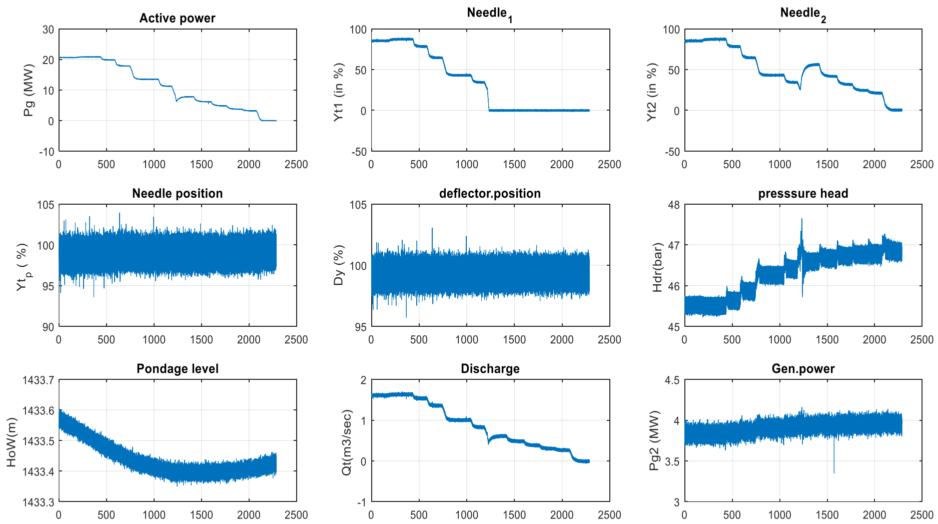


Figure 15b: Signal responses when the load is reduced in steps.

2. Load Throw-off test

The load throw-off test was conducted at 11.94 MW to determine responses of needle and deflector actions in preventing the machine from runaway speed when its load is suddenly removed. The responses of various signals to the sudden removal of load are shown in Figure 16.

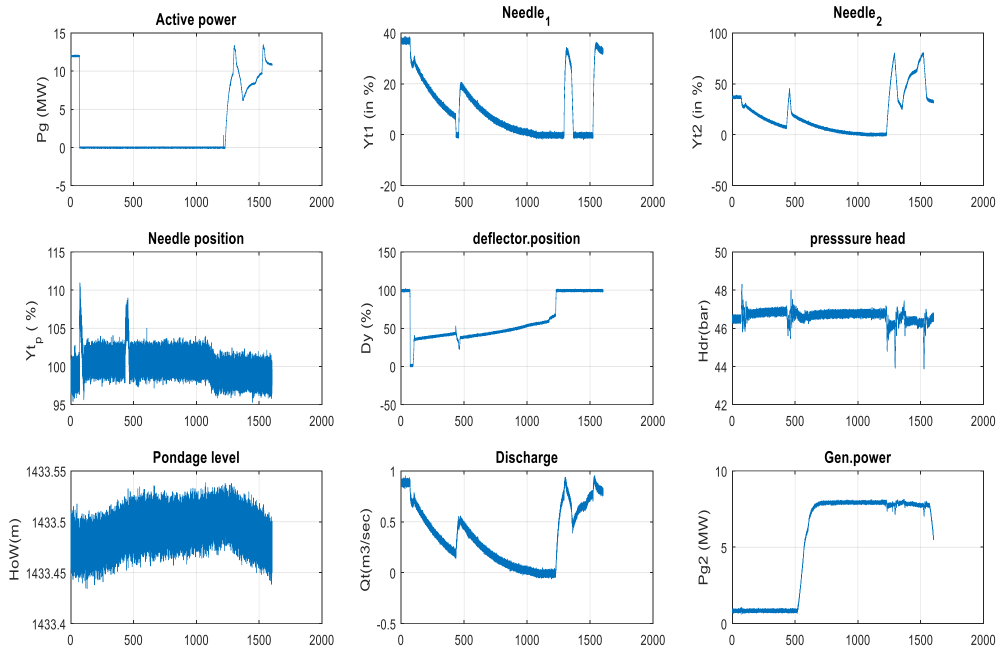


Figure 16: Shows the responses of the needle and deflector to the load throw-off test

3. Unit Emergency Shutdown test

With an initial load of 10.77 MW, an emergency shutdown of Unit was performed, and the rapid action of the deflector was observed, followed by immediate closure of the main inlet valve (Figure 17).

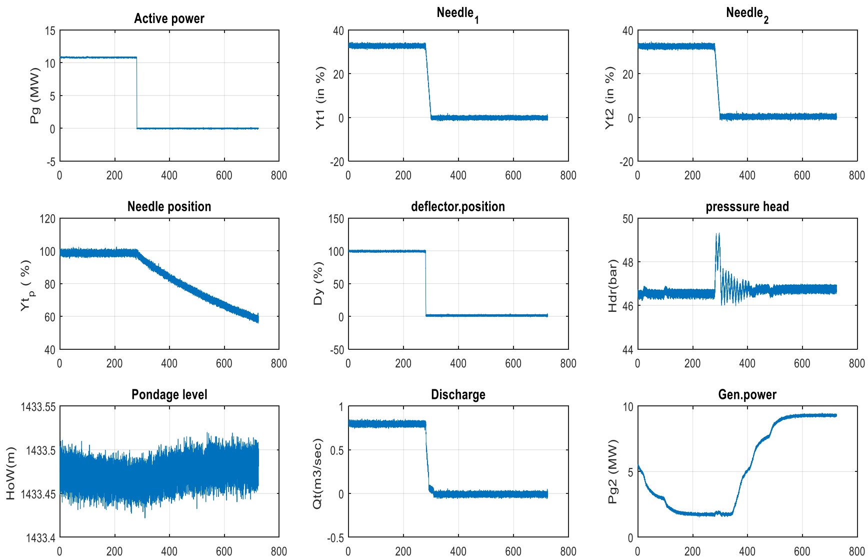


Figure 17: Reponses of needle, deflector, and pressure head at emergency shutdown.

4. Unit Restoration test

The test unit was restarted and brought to its nominal power and frequency, before being synchronized with the grid and performance measurements were recorded from standstill to full restoration (Figure 18).

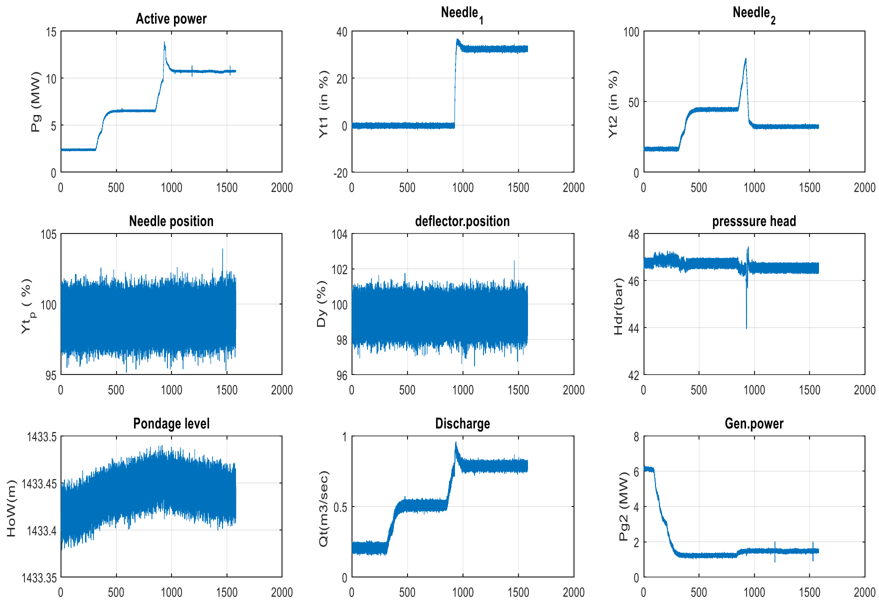


Figure18: Active power, needles, and pressure head responses of unit restoration.

5. Islanding Mode Operation test

The minimum load required for islanding must be equal to the rated nominal power of the test unit, or lower load is preferred for the survivability of test unit in island operation (Holst, et al., 2007). The test unit is connected to the western grid via a 220kV BHP-Semtokha interconnection (Thimphu feeder), while the upper stage feeds a 220kV line to Tsirang and the local station supply. The midnight load (approximately 9 MW) of Thimphu was arranged for island operation taking into account for minimal power disruption. The test Unit was gradually set to its nominal speed and the tie-breaker was opened abruptly disconnecting the unit from the grid. As expected, the active power instantly dropped to 9 MW and remained stable thereafter, indicating that the island-mode operation was under control.

The islanding operation was continued for 15 minutes for the necessary observations and recordings before normalizing the unit. Figure 19 shows the output responses of the various signals during the islanding operation.

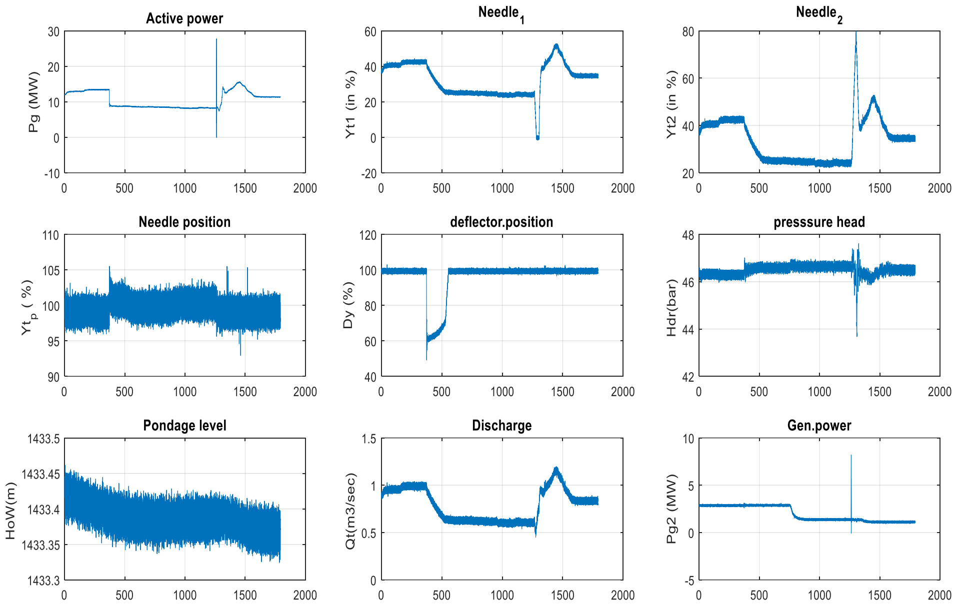


Figure 19: Active power, needles, and deflector response during islanding.

Estimation of unknown Parameters from Measurement files

Data analysis requires steps such as selecting appropriate measurement file based on test type, converting to suitable format, correcting errors and offsets, extracting stationary points, and creating a data table. A total of 18 useful measurement files were identified and rearranged according to the test sequence. Figure 20a shows a plot of stationary points from the data look-up table created by extracting the points of all signals that move or remains constant for the same length of time.

The nonlinear characteristics of the hydraulic system, such as head loss, nozzle and deflector opening functions, and the turbine operating curve, were determined from the stationary points using the iterative least squares method of curve fitting, as shown in Figure 20b to 20f.

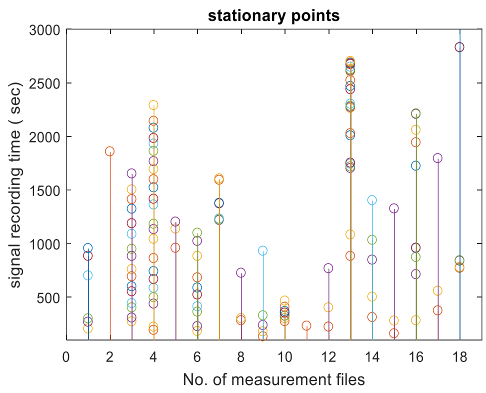


Figure 20a: Stationary points of 18 files

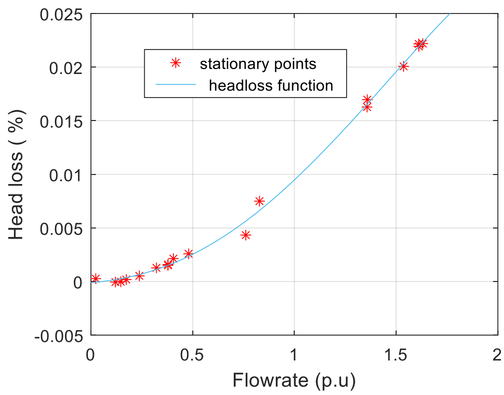


Figure 20b: Head loss function curve

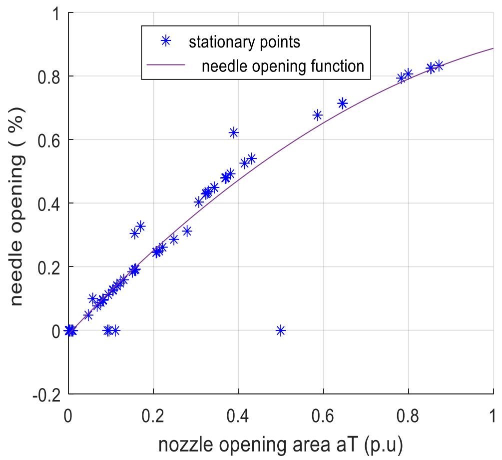


Figure 20c: nozzle opening function

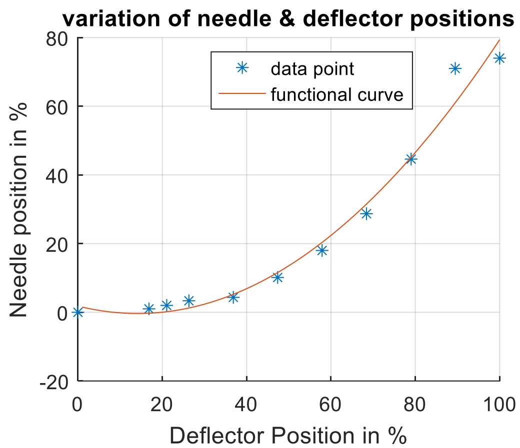


Figure 20d: needle vs deflector function

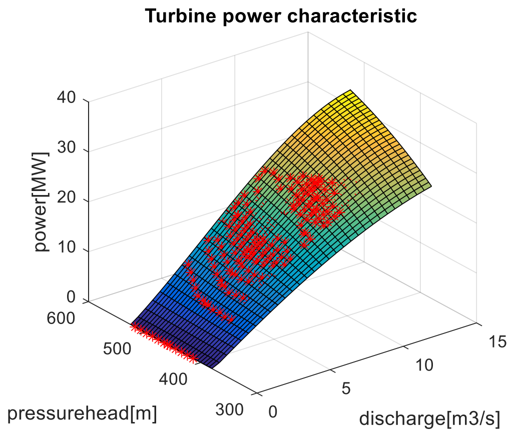


Figure 20e: BHP Turbine curve

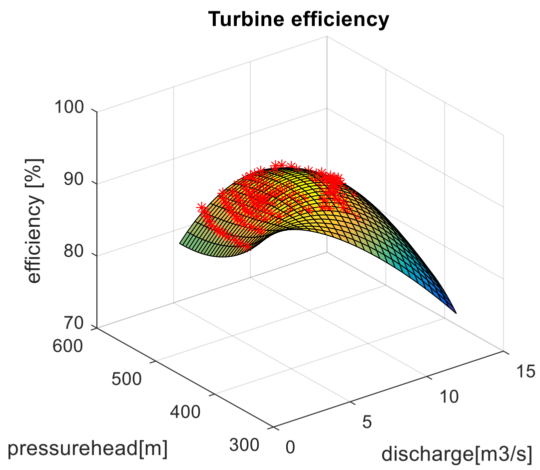


Figure 20f: BHP Turbine efficiency

Simulink/Model Validation and Discussions

The sub-models were interconnected to produce a simulation model of the entire hydraulic system (Figure 21). If the simulated results do not match the measured responses, the process and sub-mathematical models are revisited and the system parameters are fine-tuned through iterations until the simulation produces satisfactory results.

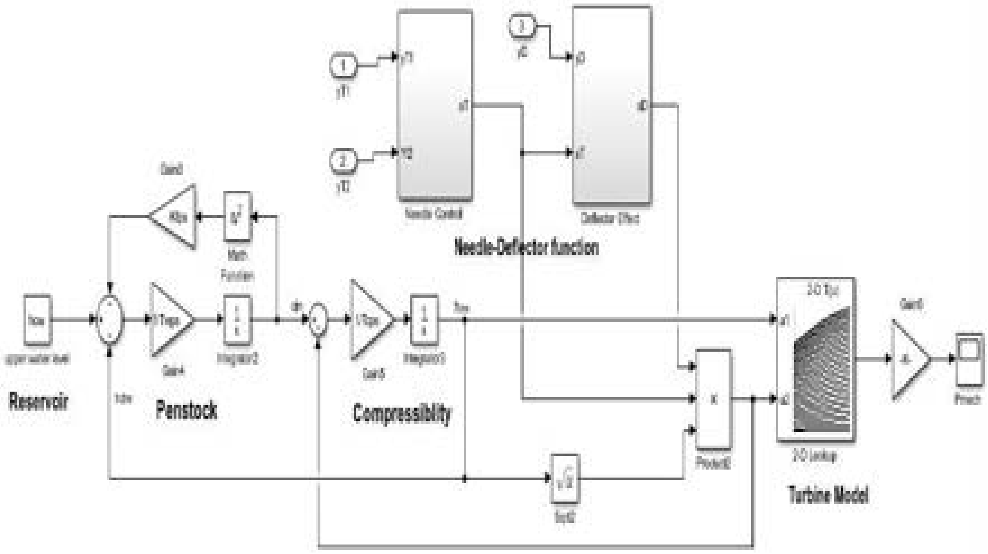
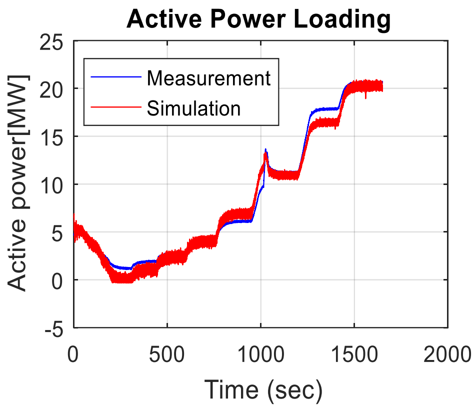


Figure 21: Simulink model of hydraulic system of BHP

Figures 22 to 25 demonstrate the validation of simulation results, with Figures 22a and 22b demonstrating the close match between the simulated and measured response of active power and needle control with the step loading of the generator from no load to full load.



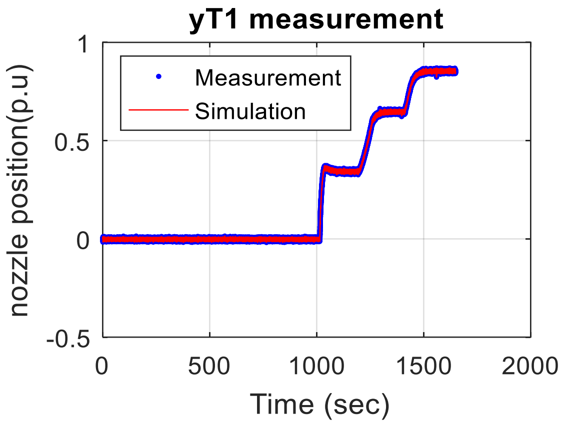
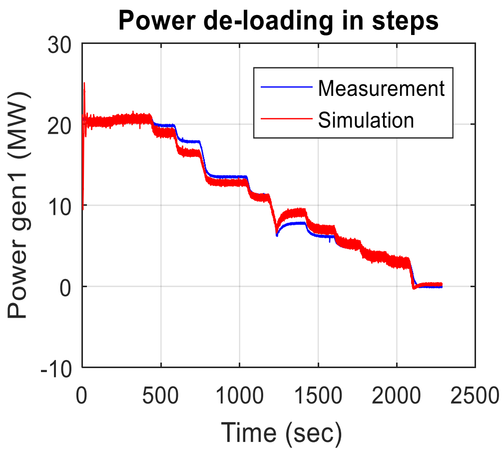


Figure 22a: Step Loading

Figure 22b: Needle response in loading

Figures 23a and 23b, on the other hand, depict the simulated responses of active power and pressure head when the load was lowered in steps from full to no load.



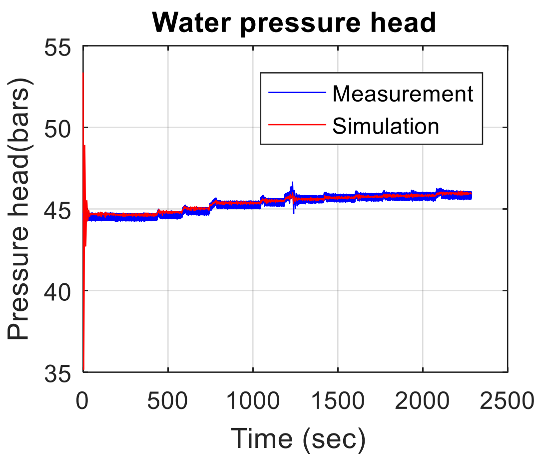
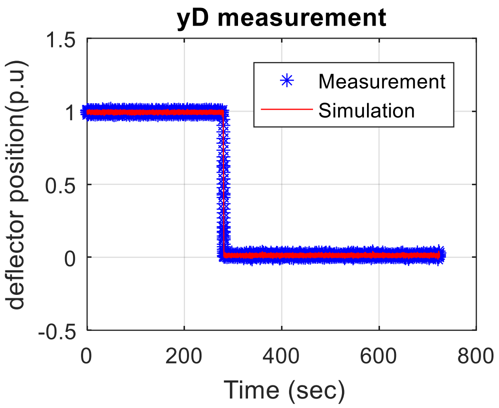


Figure 23a: step de-loading Figure

23b: pressure head response in de-loading

Figures 24a and 24b show the prompt action of defector control with the loss of active power during the emergency shutdown.



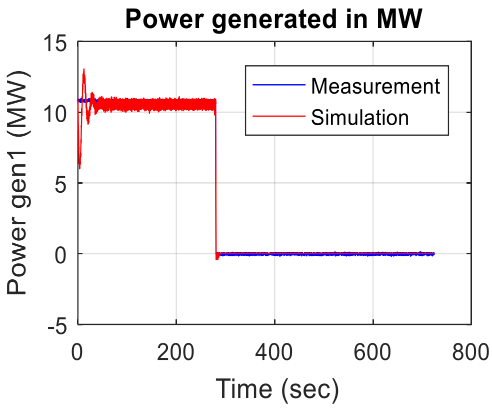


Figure 24a: Response of deflector to **Figure 24b:** Response of active power shutdown

Figure 25a shows a load throw-off test performed to observe the response of the deflector control to sudden loss of load that might occur due to faults and network instability. Figure 25b illustrates the deflector control curve for cutting off the nozzle jet at the same time as the loss of load and the immediate opening of the deflector upon unit recovery.

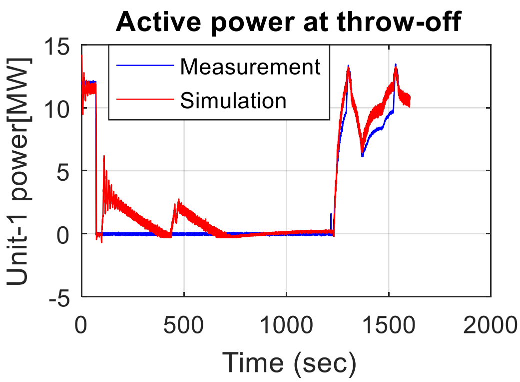


Figure 25a: Response of load-throw off

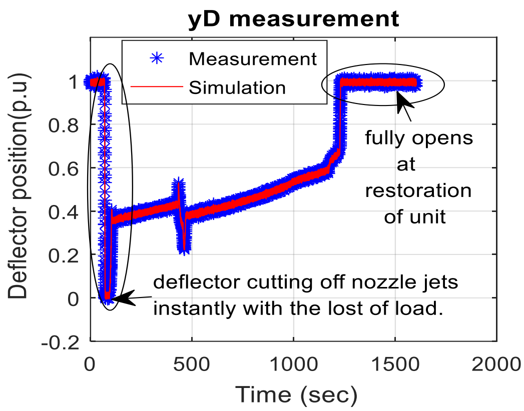
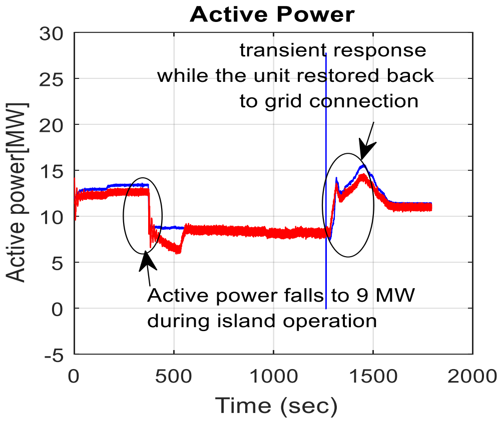


Figure 25b: response of deflector control

Observations and Analysis of the Islanding Operation

Figures 26a to 26d illustrate that the responses of essential control signals during the islanding operation. The active power of the test Unit dropped from 13 MW to 9 MW when it was abruptly unplugged from its grid (Figure 26a), and it continued to operate in island mode. Figure 26b demonstrates the high accuracy of deflector control in cutting off the nozzle jet without any delay effect. However, while restoring the Unit, the active power transient response hitting its limit, which could be related to the rapid opening of the nozzle, as shown in Figure 27c.



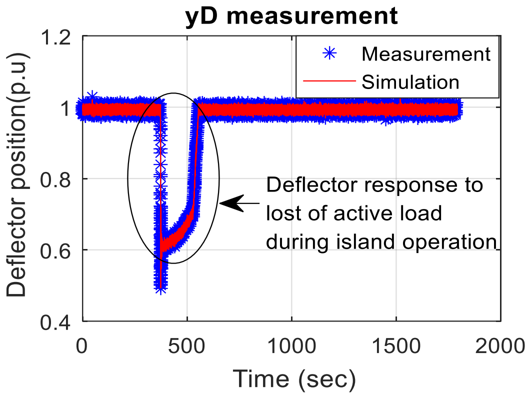
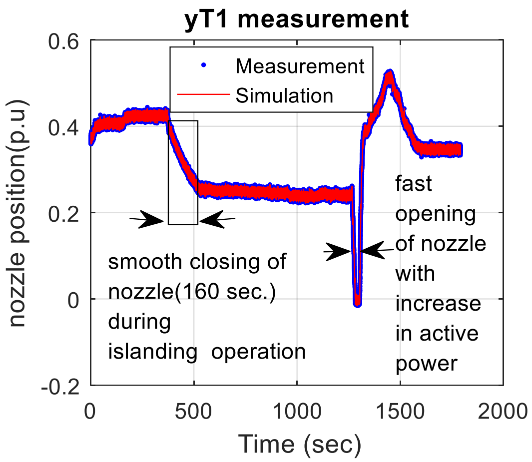


Figure 26a: Active power transition

Figure 26b: deflector action in islanding

Figure 27c shows the smooth closing of nozzle jets which took about 160 seconds to regulate the flow rate proportion to island load. The surge oscillations in the penstock and their effects are directly related to how quickly the nozzles open and close gradually with changes in active power and frequency (Figure 27d).



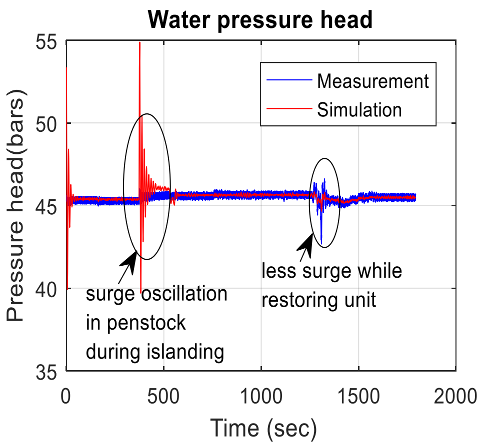


Figure 27c: Needle response, island mode

Figure 27d: Pressure head response

Conclusion and Further Scope

This paper primarily described how the mathematical modeling and simulation of BHP is constructed using a combination of the First Principles and the System Identification method. The generic mathematical model derived from the above combined method was fine-tuned using real-time measurement data and plant documentation. The composite model was then simulated and validated by comparing the simulated responses of the various signals to the measured test records.

The measurements and simulation results confirmed that the Basochhu Hydropower Plant has robust governor control systems, and it can withstand the island mode operation, and reliably feed the local load without the need for grid interconnection. The precise control of the deflector is remarkable; it instantly cuts off the water jet in response to changes in the generator output.

However, this established simulation model is limited to confirming the measured hydraulic system responses, whose dynamic and transient stability needs to be further investigated through interconnections with synchronous generator and transmission network models.

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